changes in each design variable value. Additional information and examples of the piecewise linear analysis is given in reference 15.

ROTOR BLADE AERODYNAMIC DESIGN

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This section of the paper deals with the aerodynamic performance aspects of rotor blade design. Design considerations, aerodynamic constraints and design variables are described.

Design Considerations

An important aspect of aerodynamic design of a helicopter rotor blade is the selection of the airfoils which could be applied over various regions of the blade radius. The choice of airfoils is controlled by the need to avoid exceeding the section drag divergence Mach number on the advancing side of the rotor disc, avoid exceeding the maximum section lift coefficients on the retreating side of the rotor disc, and avoid high oscillatory pitching moments on either side of the rotor disc. Since airfoils with high maximum lift coefficients are advantageous in high speed forward flight and pull-up maneuvers, high lift sections are generally used from the rotor blade root out to the radial station where the advancing side drag divergence Mach number precludes the use of the section. From that station outward, other airfoil sections which have higher drag rise Mach numbers are used.

Once the airfoils and an initial airfoil distribution are selected, the induced and profile power components become functions of twist, taper ratio, point of taper initiation, and blade root chord (ref. 16). For the hover condition, the majority of the power is induced power and the remainder is profile power. Rotor blade designs which minimize both induced and profile power are desirable. The induced power is a function of blade radius, chord, and section lift coefficient. The profile power is a function of blade radius, chord, and section drag coefficient. The induced and profile power can be reduced (provided the aerodynamics of all retreating blade

air-foils are within linear theory) by increasing taper ratio and/or blade twist - both of which tend to increase inboard loading and decrease tip loading. Configurations which increase tip loading may be efficient at very high speeds under certain design constraints (such as a maximum allowable blade radius) but these kinds of configurations will not be considered in phase 1 of this activity.

Satisfactory aerodynamic performance is defined by three requirements. First, the required horsepower for all flight conditions (see eq. 1) must not exceed the available horsepower. Second, airfoil section stall along the rotor blade must be avoided for any forward flight operating condition, i.e. the airfoil sections distributed along the rotor blade must operate at section drag coefficients less than a specified value (neglecting the large drag coefficients in the reverse flow region). Third, the helicopter must be trimmed in forward flight.

Rotor Blade Aerodynamic Constraints

The first design requirement translates into five constraints of the type shown below. BY CONMIN sign convention, a constraint g_i is satisfied if it is negative or zero and violated if it is positive.

$$g_1 = HP_r/HP_a - 1 \qquad \text{hover} \tag{4}$$

$$g_2 = HP_r/HP_a - 1 \qquad \text{cruise} \tag{5}$$

$$g_3 = HP_r/HP_a - 1 \qquad \text{high speed} \tag{6}$$

$$g_4 = HP_r/HP_a - 1 \qquad \text{maneuver} \tag{7}$$

$$g_5 = HP_r/HP_a - 1 \qquad \text{climb} \tag{8}$$

where HP_r and HP_a are the total horsepower required and the total horsepower available for the main rotor, respectively.

The second design requirement - that airfoil section stall not occur - translates into constraints on the airfoil section drag coefficient (c_d) at various

azimuthal angles for the various flight conditions. At a given azimuthal angle ψ the constraint is formulated as follows:

$$g = \left(c_{d_{1,\psi}} / c_{d_{max}}\right) - 1 \tag{9}$$

where $c_{d_{max}}$ is the maximum allowable drag coefficient and $c_{d_{1,\psi}}$ is the largest drag coefficient along the blade radius outside the reverse flow region at a given azimuthal angle (see figure 4).

The third design requirement, that the helicopter must be trimmed for each forward flight condition, is somewhat difficult to translate into a continuous mathematical programming constraint. This constraint is implemented by determining from the aerodynamic analysis whether or not, at a specified velocity, the helicopter can trim at the specified gross weight.

Analyses

Two analysis computer programs are used to predict rotor performance. The hover analysis denoted HOVT (which uses a strip theory momentum analysis, described in ref. 16 and ref. 17) will be used to compute hover and climb horsepower. The CAMRAD program (ref. 14) will be used to define the trim condition, the horsepower required in forward flight, and the airfoil section drag coefficients for the forward flight and maneuver conditions. Both analyses use tables of experimental two-dimensional airfoil data. The choice of CAMRAD was based on several considerations. First, CAMRAD is being coupled with computational fluid dynamics (CFD) analyses which will result in better modeling of transonic and other effects (ref. 18); replacing CAMRAD with a CFD-coupled version of CAMRAD should cause a minimum amount of changes to the total optimization program compared to the substitution of an entirely different global performance analysis. Second, CAMRAD was selected for the loads and stability computations, so using it for the forward flight aerodynamic analysis streamlines the overall analysis flow. The hover performance trends predicted by HOVT have been

verified by model tests of both advanced and baseline designs for the UH-1, AH-64, and UH-60 helicopters (refs. 19-22). A more sophisticated hover analysis which includes wake effects may be used in the future if the trends predicted by such an analysis are verified for a wide range of configurations, i.e., different taper ratios, taper initiation points, twist distributions, etc.

ROTOR BLADE DYNAMIC DESIGN

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Design Considerations

The rotor dynamic design considerations are essentially limitations on the vibratory response of the blades which in turn limit the dynamic excitation of the fuselage by forces and moments transmitted to the hub. The following quantities associated with the blade response are subject to design constraints: blade frequencies, vertical and inplane hub shear, rolling and pitching moments, and aeroelastic stability margin.

Frequencies.- The blade natural frequencies are required to be separated from multiples of the rotor speed. A typical constraint is written as

$$\omega_{Li} \leq \omega_i \leq \omega_{ui} \tag{10}$$

where ω_i is a blade frequency, and ω_{Li}, ω_{ui} are lower and upper bounds of the ith frequency. Generally, ω_{Li} and ω_{ui} are $n\,\Omega \pm \delta$ where n is an integer, Ω is the rotor speed, and δ is a tolerance usually about 10 percent of $n\Omega$ (e.g., ref. 6).

Vertical hub shear.- The transmitted vertical hub shear S is to be made as small as possible. This requirement may be handled either as part of the objective function wherein it is minimized (ref. 6), or as a constraint where the vertical hub shear is required to be less than some specified value (ref. 23). In the first approach, letting N denote the number of blades in the rotor